The impact of astrophysical distributions on supernova (and gravitational wave) cosmology

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With help from Duke Cosmology

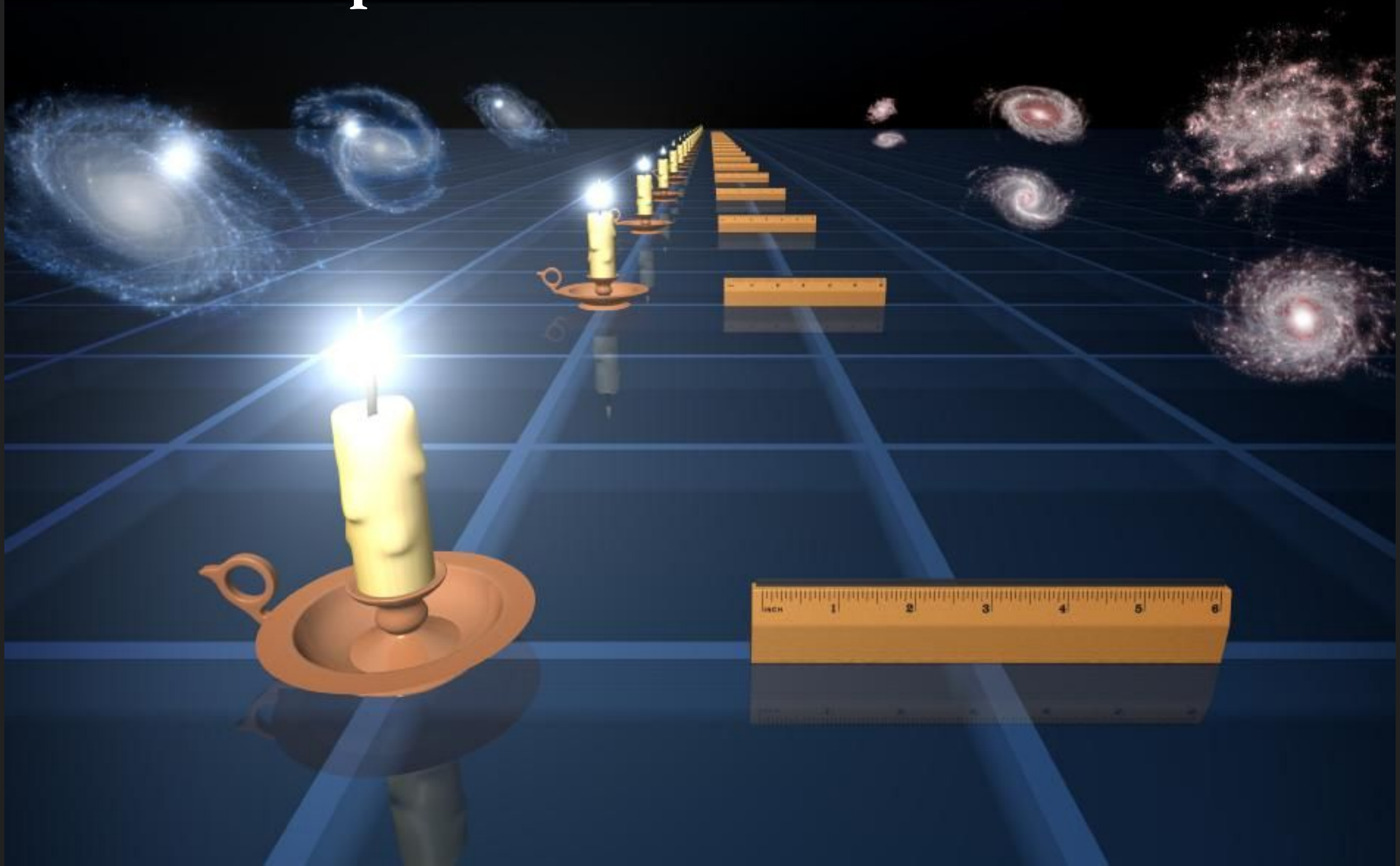
Supernovae as distance measurements

- Distance measurement tracking expansion history of the universe
- Standard candles
- Need follow-up (mostly!)
- Relative distance
- Impacted by selection effects

Gravitational Waves as distance measurements

- Distance measurement tracking expansion history of the universe
- Standard ~~candles~~ sirens
- Need follow-up (mostly!)
- ~~Relative distance~~ *Absolute* distance
- <u>Impacted by selection effects</u>

Supernovae - Relative Distance



What I do - map the evolution of the universe with Type Ia supernovae

- Standard candles
- A white dwarf star accretes matter from *something* before exploding
- Always explodes near the same mass
- This makes it pretty standardised
- But we don't know the *exact* explosion mechanism - hence relative distance

- Needs a redshift (preferably spectroscopic)

So how do we get a redshift?

Two ways:

1. Acquire spectroscopy from the supernovae as it happens (tough)
2. Get host-galaxy spectra after the event with follow-up (easier)
   a. Can get redshifts long after the supernova - only difficulty is assigning the right galaxy.
   b. This is the same methodology for kilonovae
   c. Turns out we get the host galaxy right pretty frequently (Popovic et al. 2020)

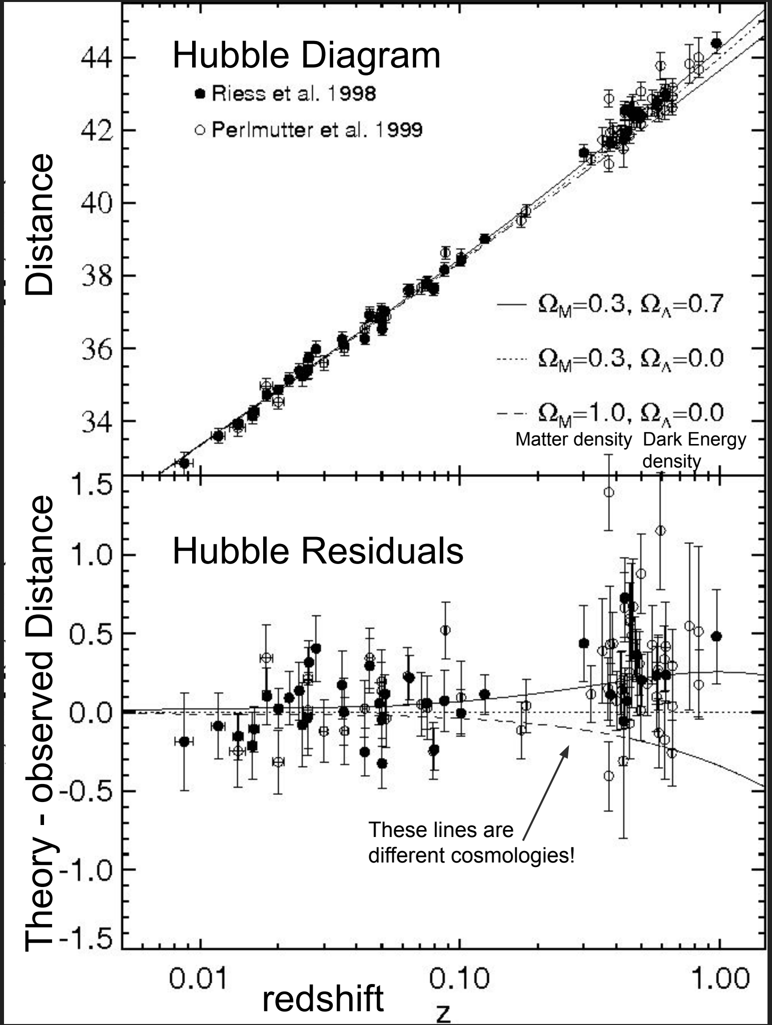
Both approaches have their own pros and cons…

What do we do with this?

Back in 1998 we were pretty sure that the universe was decelerating.

We had 10s of supernovae and some redshifts.

This is a Hubble Diagram: shows distance (y-axis) as a function of redshift (x-axis). This is the key plot for SNIa - can compare to theoretical cosmologies from this!



What is Dark Energy?

Comprises most of the universe

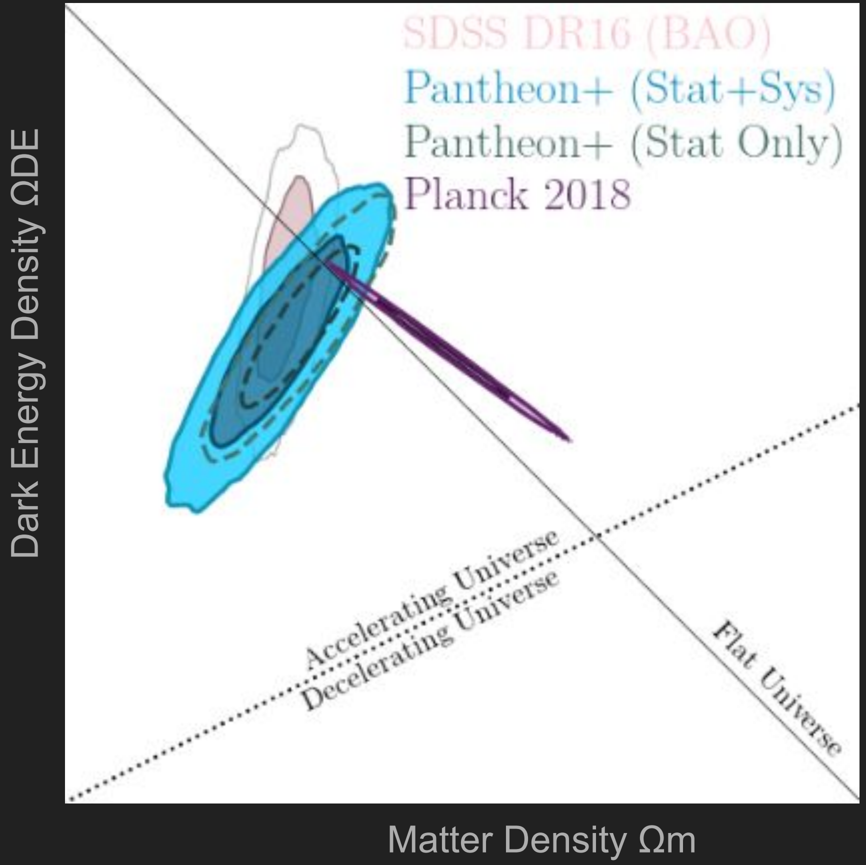
We don’t really know what it is

$$H^2 = H_0^2(\Omega_m(1+z)^3 + \Omega_{DE}\exp(3\int_0^z \frac{dz}{1+z}(1+w)))$$

$$H = (1+z)^{-1} * \frac{d(1+z)^{-1}}{dt}$$

But we know that the nature of Dark Energy with time can be characterised by *w*!

The value of *w* determines the eventual fate of the universe



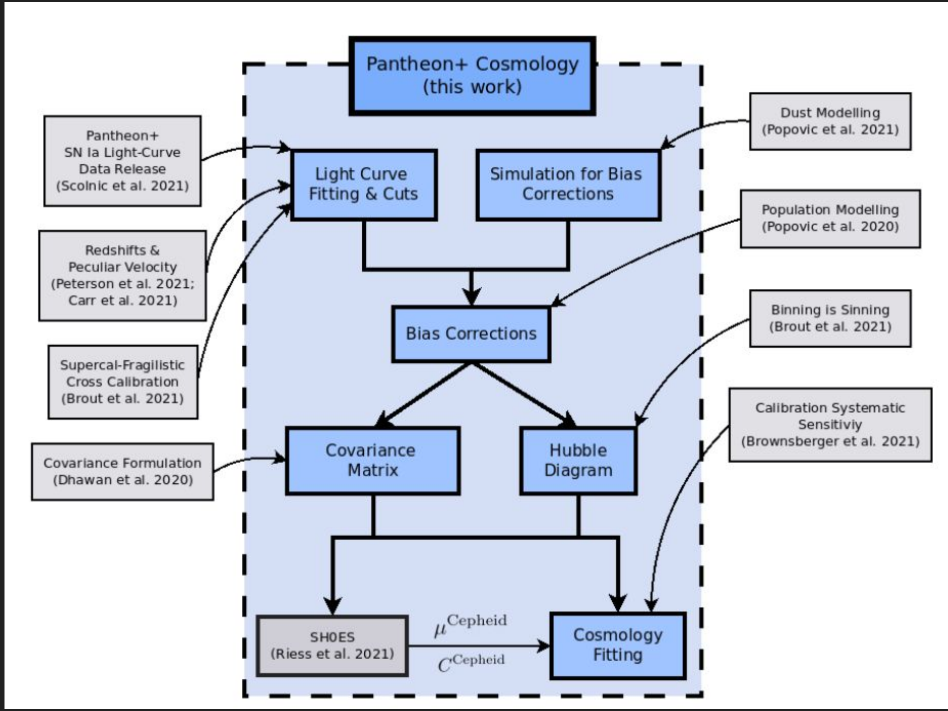
Brout, Scolnic, Popovic et al. 2022

SNIa cosmology has gotten significantly more complicated

Introducing Pantheon+

A set of 10 interconnected papers that constitute the most accurate measurement of *w* and H0 to-date.

Methodology has become considerably more complex - cross calibration, modeling, covariances, bias corrections, redshifts, peculiar velocities



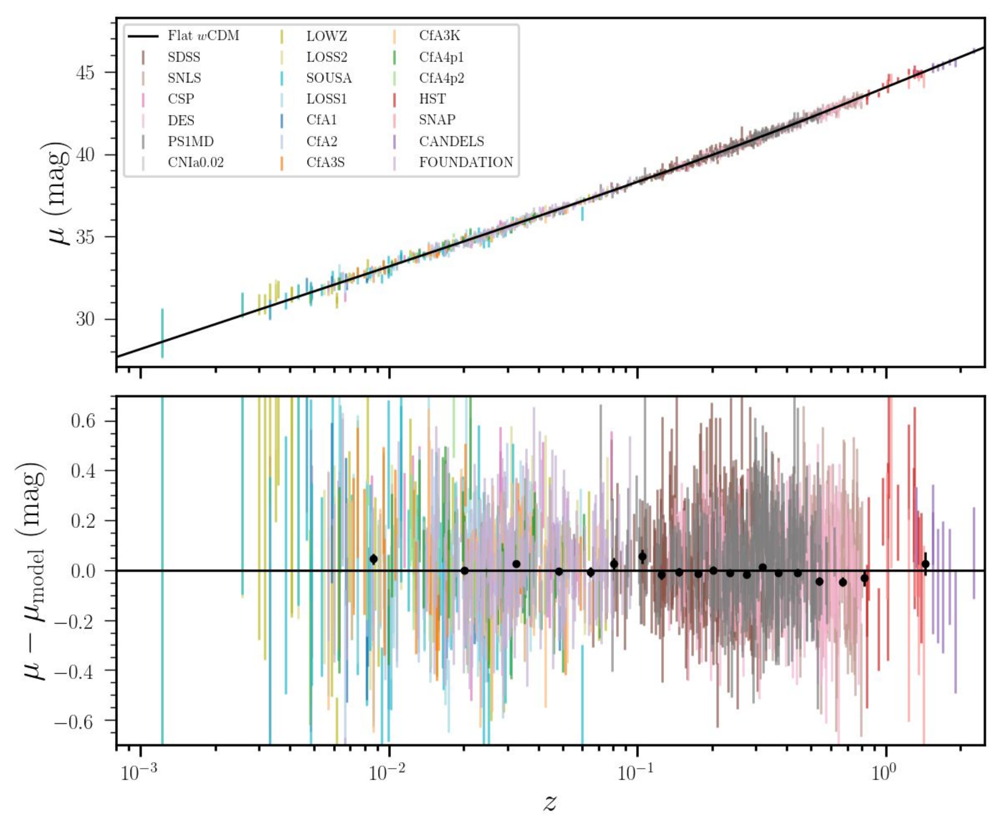
Brout, Scolnic, Popovic et al. 2022

What does SNIa cosmology today look like?

Today, we have thousands of supernovae

We're still looking at statistical uncertainties on the order of ~3%

Does *w* change with redshift? Still unable to tell! Need more statistics and more reductions in systematic uncertainties!



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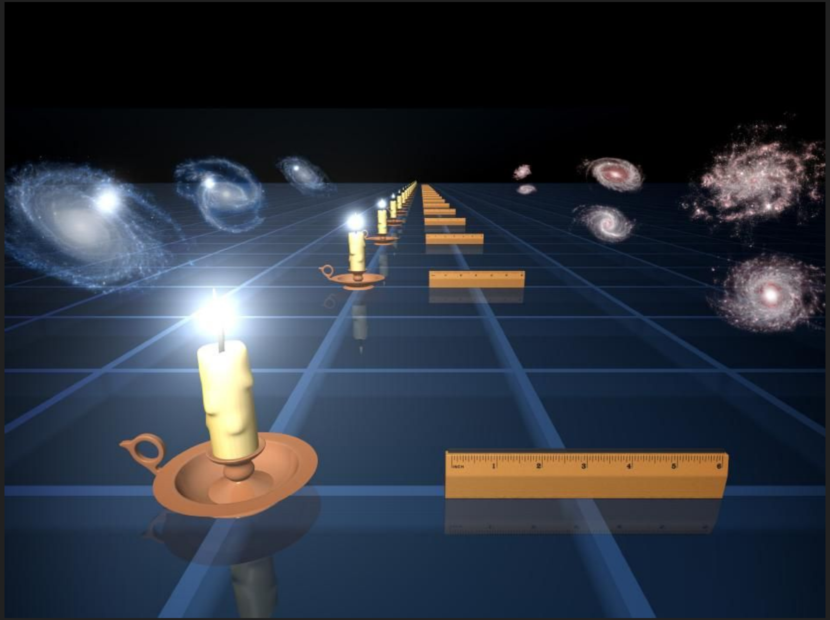
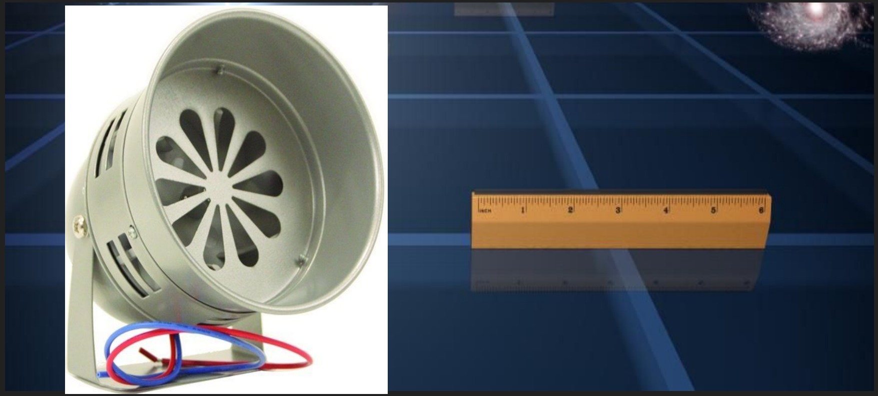
Gravitational Waves - Absolute Distance

Recall that we need more than one supernova to get distance - we compare luminosity as a function of redshift!



Since the GW explosion mechanism is well known, only one GW is needed for absolute distance



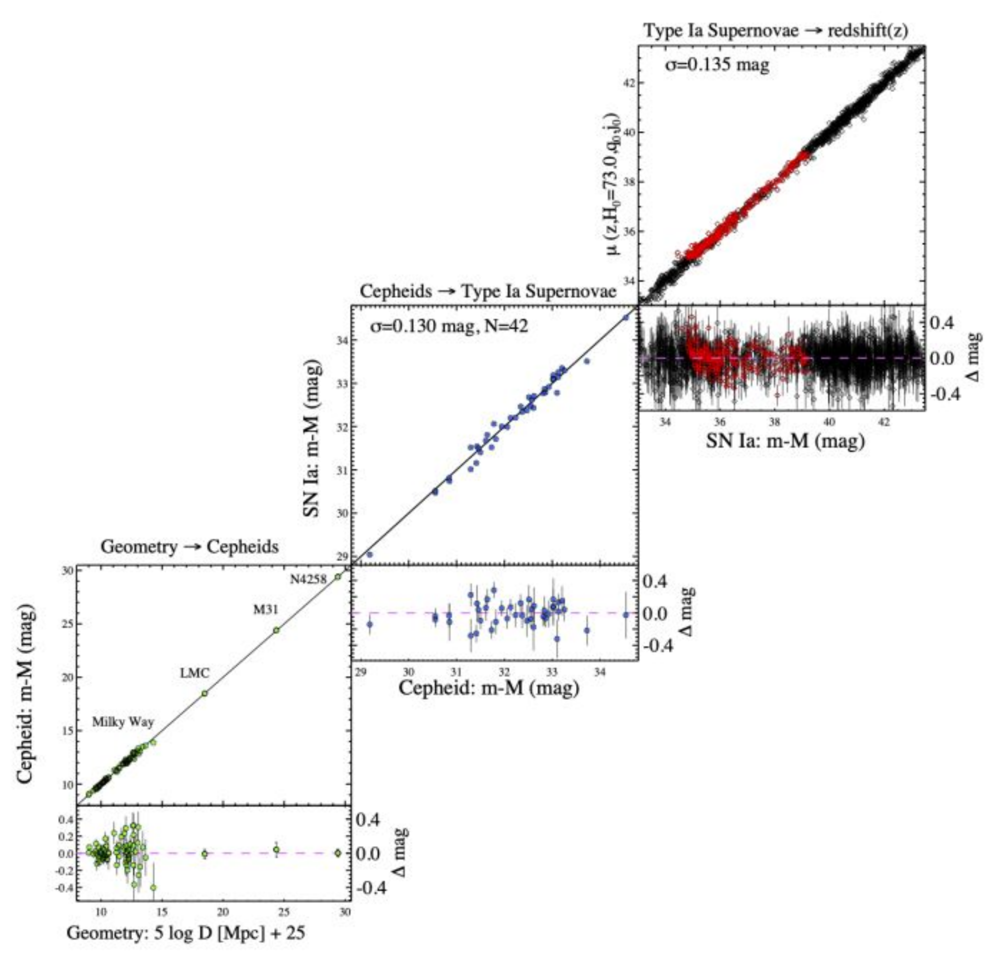
How do we get absolute distance for Supernovae?

We need to take several steps:

1. Geometry
2. Cepheids
3. Supernovae

We have about 40 supernovae in the second rung, 300 in the final rung

All the supernova in the universe would not tell us H0 on their own!



Riess et al. 2021

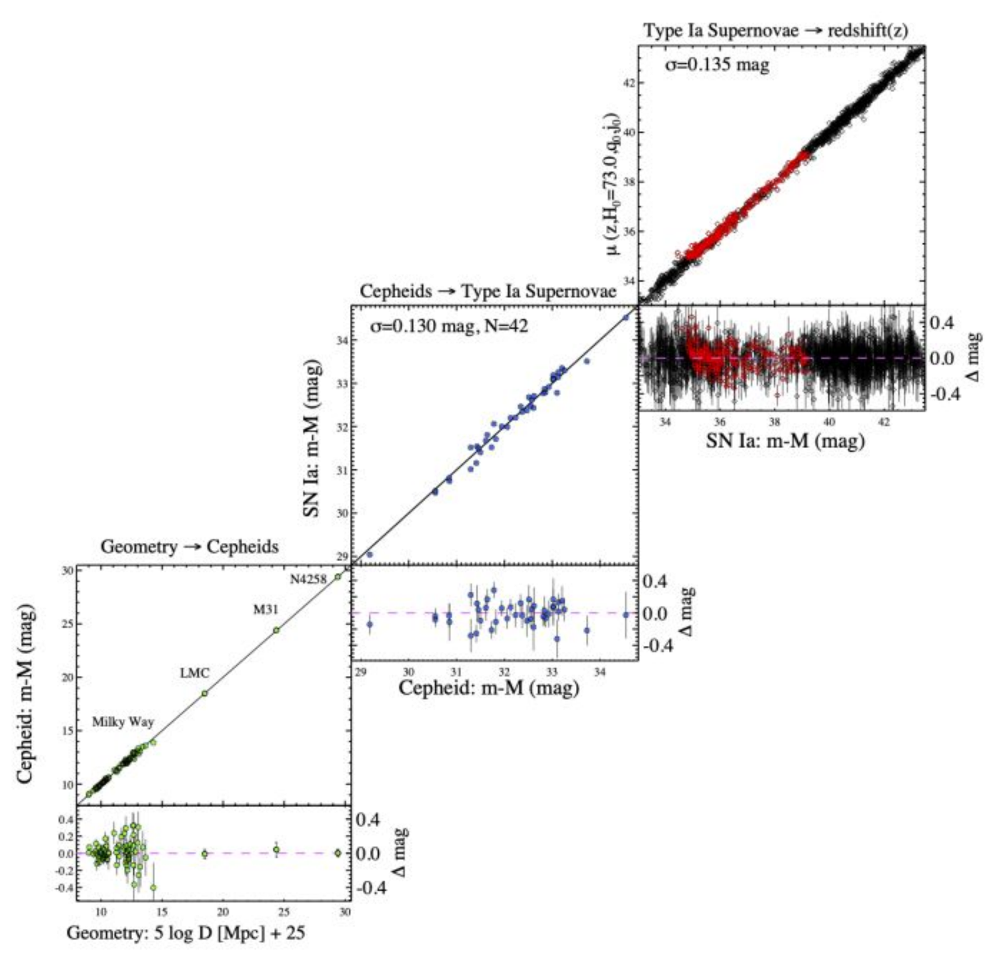
Supernovae and H0

Tying together all these disparate methods is difficult!

The SH0ES team has done an amazing job, but...

You may have heard of the controversy surrounding H0...

67.4 +/- 0.5 km/s/Mpc
69.8 +/- 10 km/s/Mpc
73.0 +/- 1.04 km/s/Mpc
Current tension is 5 sigma!



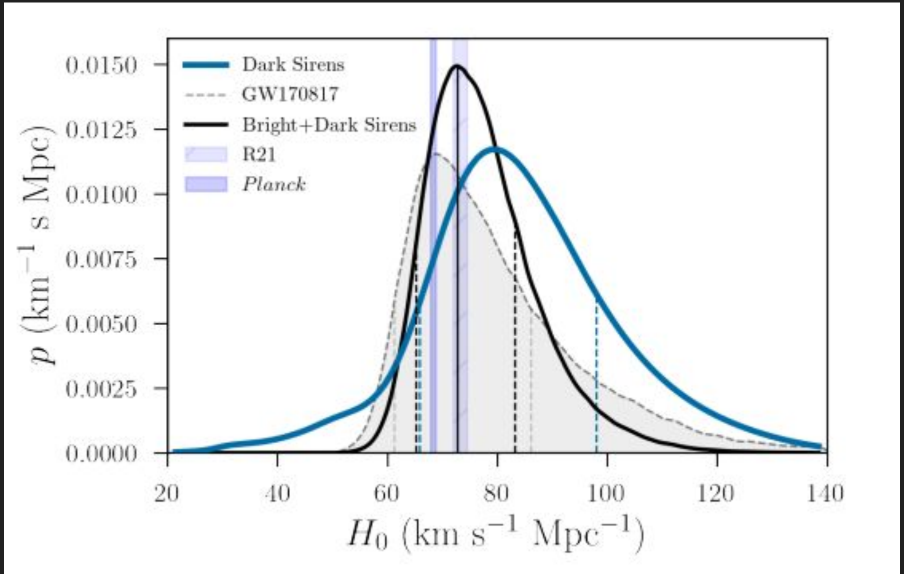
Riess et al. 2021

Gravitational Waves and H0

- Tens of GW to get a competitive H0 signal
- Direct distance measurement - one GW and EM followup are all you need!
- Incredibly impressive!

Only caveat is that this precision relies on Bright Sirens

- But we can use Dark Sirens as well!
- Posterior is much broader - let's investigate that a little further



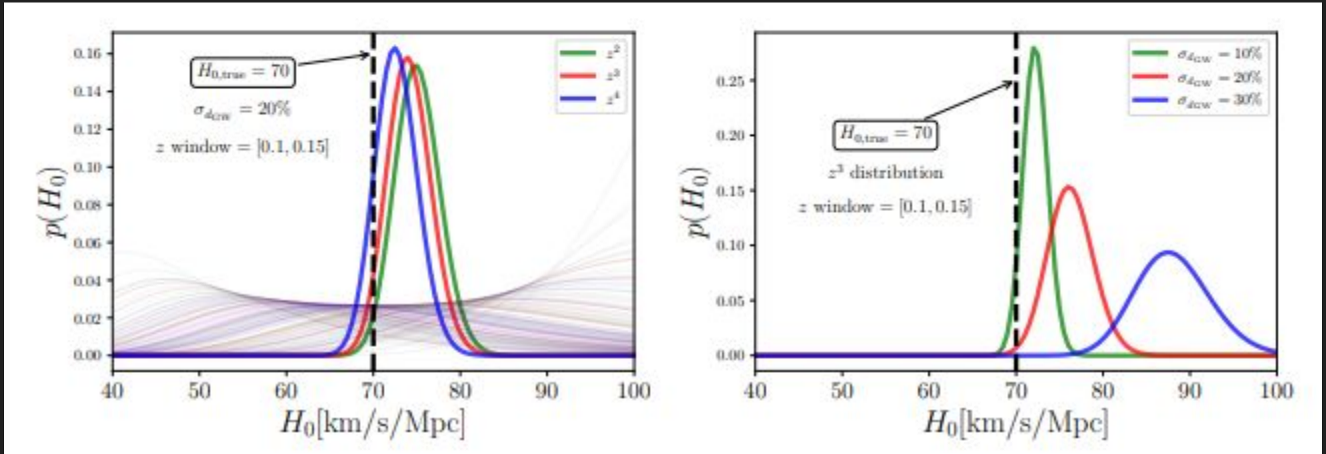
Palmese et al. 2021

Dark Sirens need stronger priors

Astrophysical distributions can impact cosmology measurements.

How are we going to reduce uncertainty in dark sirens? There's a giant dataset that will just be waiting to be used!

But we need to know more about the universe, populations, and statistics



Trott Huterer 2021

How have other fields dealt with this problem?

1. Large set of data
2. Impossible to analyse on a per-event basis
3. Populations that inhere in the Universe itself can affect the measurements

This is what I do! I've been studying the impact of astrophysical populations and selection effects on supernova measurements and cosmology!

We have simulations, data, but we need a model

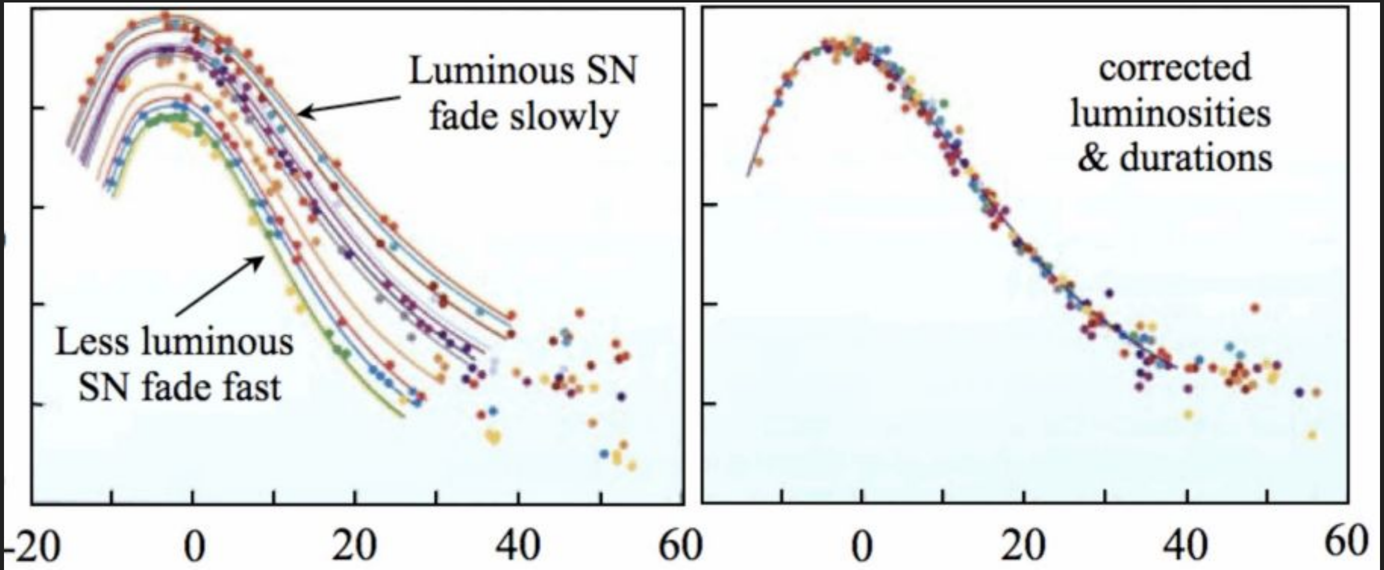
1. Measuring Distances
2. Supernovae are not independent of their host galaxy
3. Explaining the unexplained scatter in supernova
4. Simulation and Simulacra
5. Inferring un-observable distributions from observable data
6. Impact on Cosmology

Measuring Distances

Supernova are *standardisable* candles

The thing that makes SNIa useful is that they're *standardisable* - before standardisation, we have a dispersion of about 0.5 mag, reduced to 0.1 mag afterwards!

Without standardisation, SNIa are almost useless as a probe.



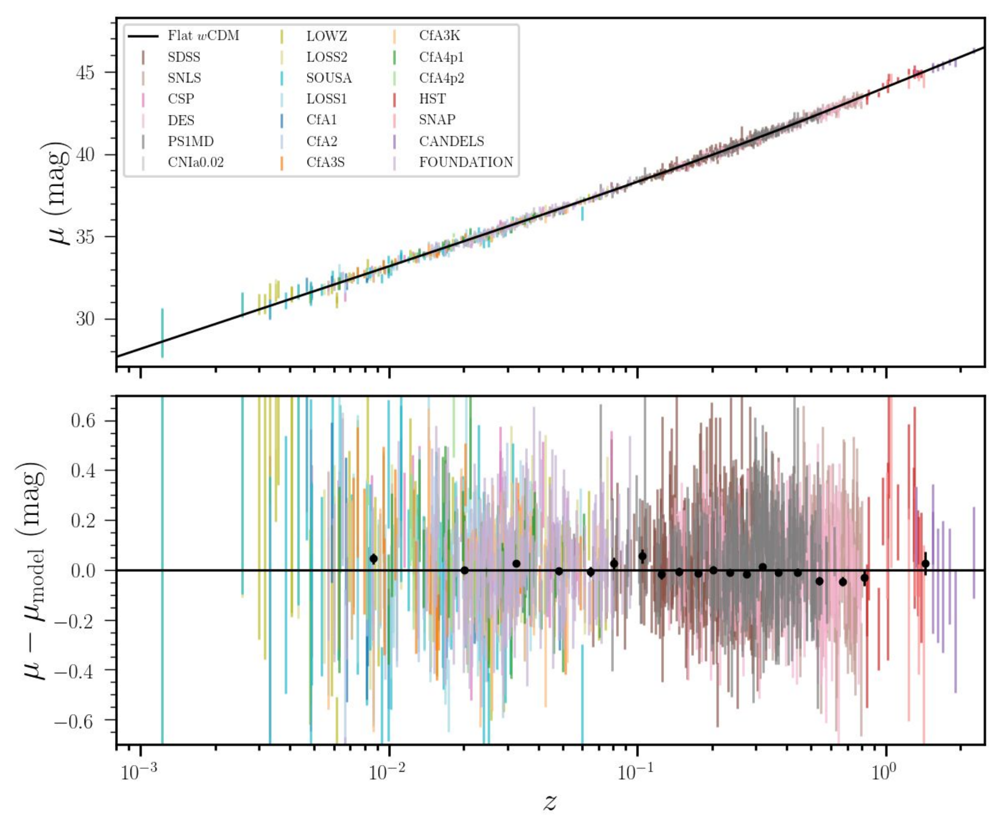
$$\mu = m_B - \beta c + \alpha x_1 - M_0$$

Standardising SNIa

$$\mu = m_B - \beta c + \alpha x_1 - M_0$$

mB is the log of the light-curve amplitude
c (‘colour’) is related to astronomical colour
x1 (‘stretch’) is related to light-curve width

We standardise on 3 *observable* parameters.



Brout, Scolnic, Popovic et al. 2022

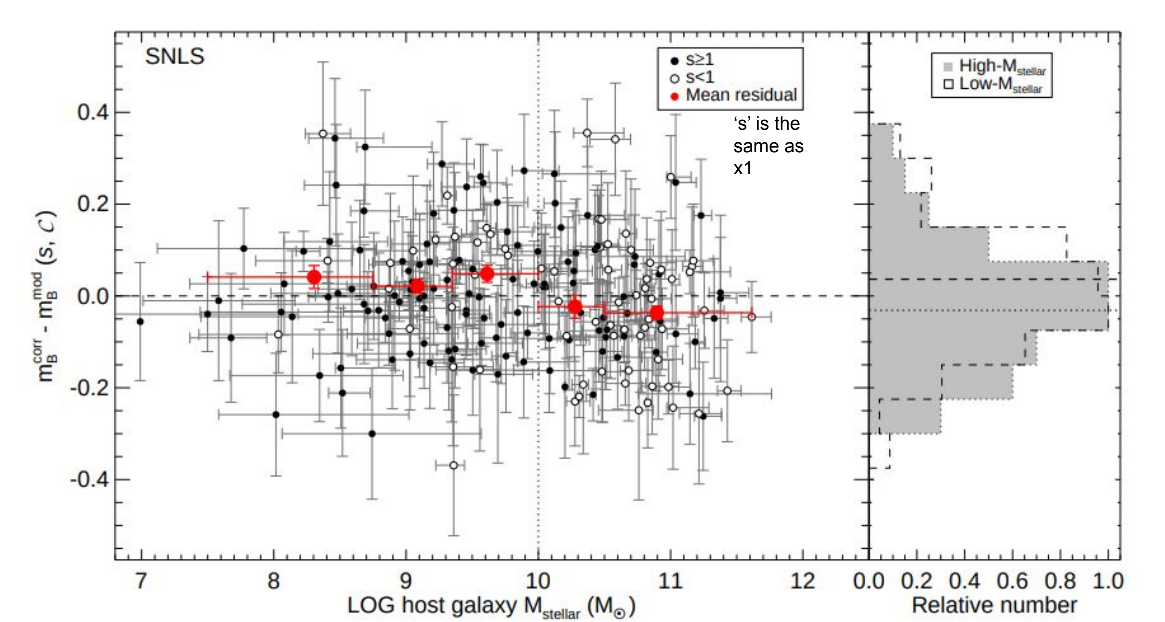
Supernovae are not independent of their host galaxy

Host-galaxy parameters are also involved!

We see a step function in observed distance as a function of the host-galaxy mass! This is known as the 'mass step'

Originally observed at 0.05 magnitudes - big change in cosmology!

Well outside of error, and kept showing up for the next decade!



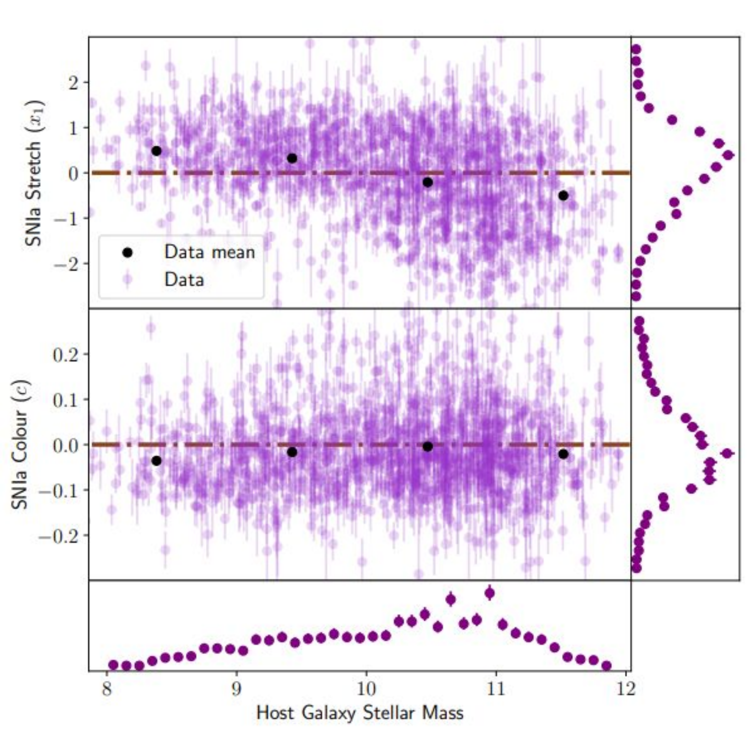
Sullivan et. al 2011

Our observed parameters depend on their host-galaxy

Turns out there are actually 4 parameters!

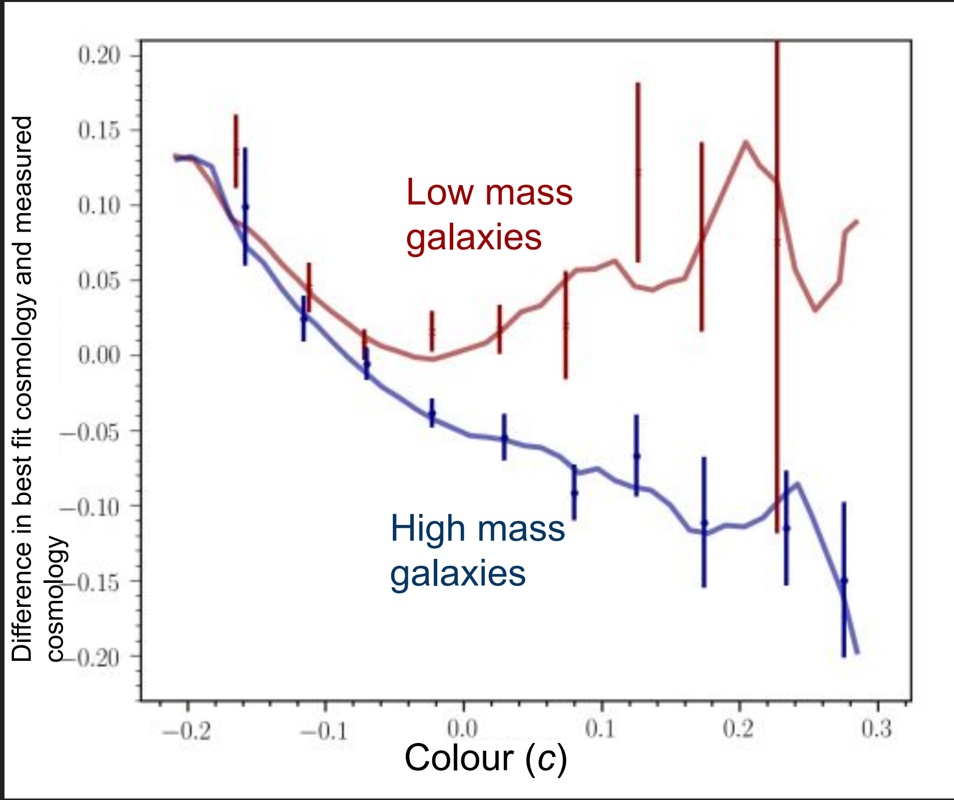
Both stretch and colour correlate with the mass of the host-galaxy!

This puts the burden on us to learn about the host-galaxy: *supernovae are not independent of their hosts!*



Popovic et al. 2021a

Speaking of colour



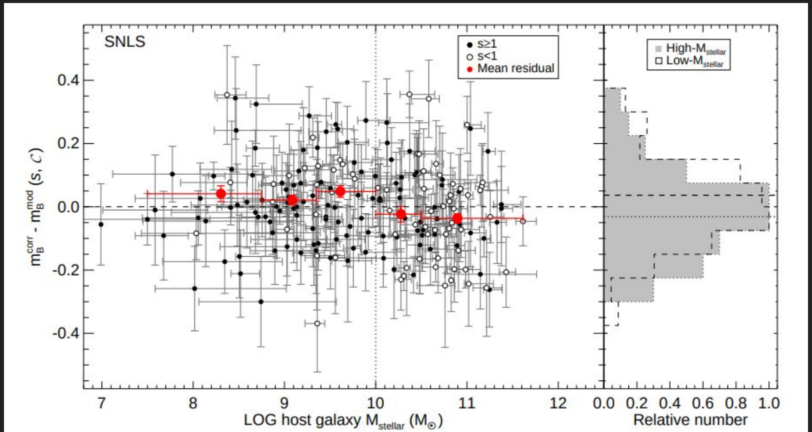
Let's take a look at some Hubble Residuals: the difference between best fit cosmology and our measured cosmology!

If we split these Hubble Residuals on host-galaxy mass, we can see that the Hubble Residuals change as a function of colour!

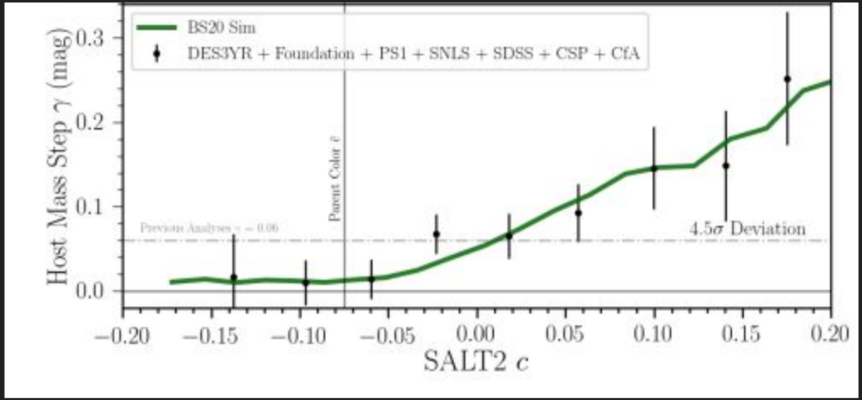
Fairly drastically too - why is this happening?

Brout Scolnic, 2021

Speaking of colour: The Mass Step



Sullivan et. al 2011



Brout Scolnic, 2021

The Mass Step gets bigger
with increasing colour!

Explaining the unexplained scatter in supernovae

What if our observed parameters are not the real ones?

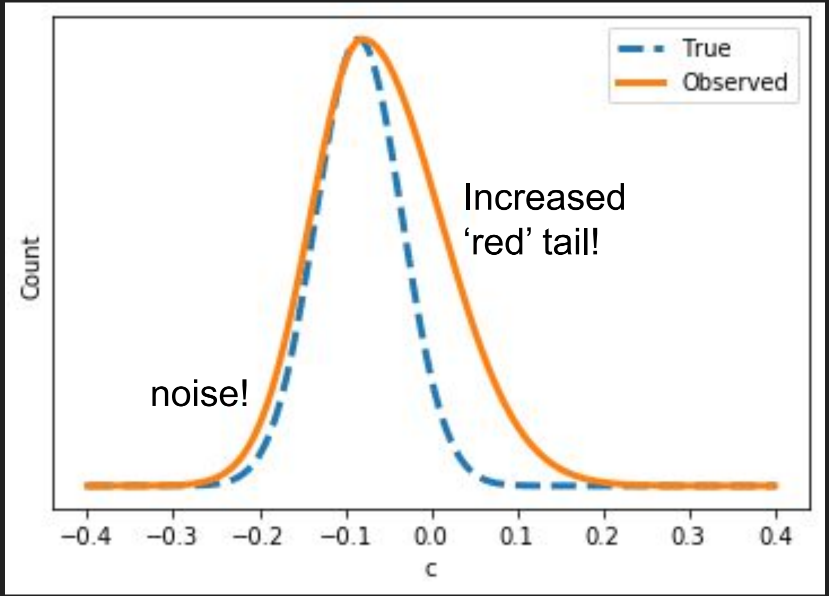
Let's take *c* - it's effectively astronomical colour (a difference in light between two bands in our telescope)

Selection effects, dust, environmental effects, non-cosmological reddening - these can all bias our observed colour.

What if our observed c is not the 'true' c?

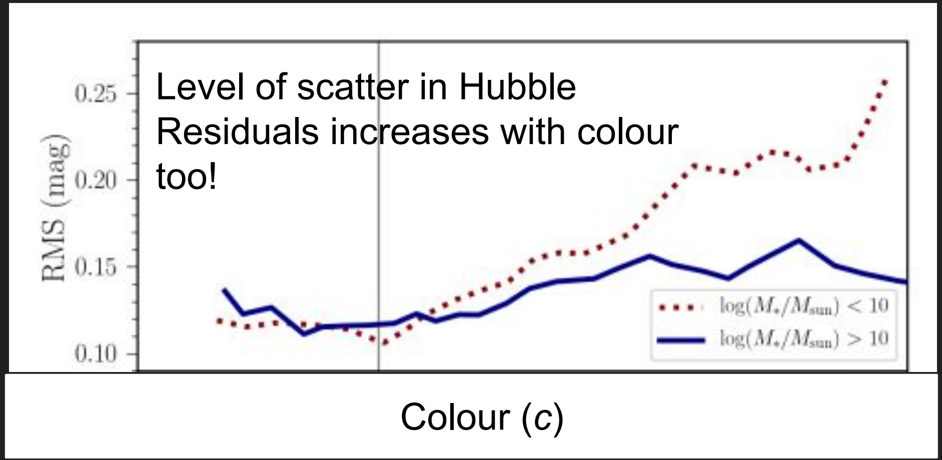
This would be degenerate with distance

Much like inclination...



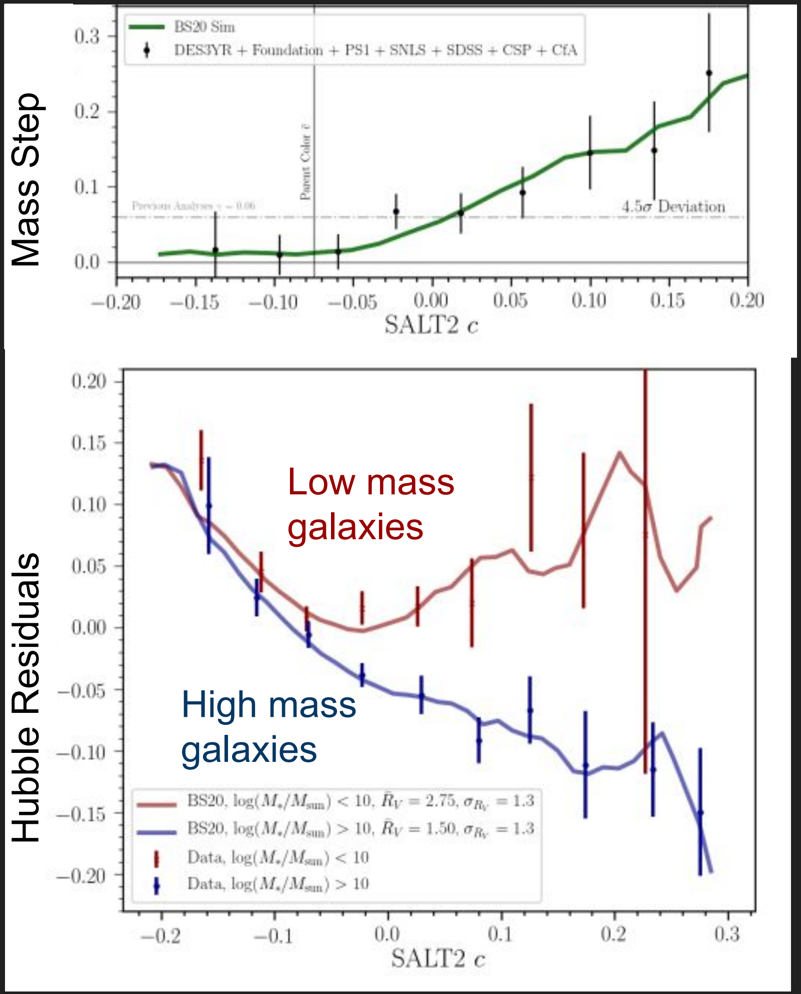
Popovic et al. 2021a

What is the cause of these trends?



A lot of disparate pieces pointing to something

I feel like a blind man, and this is a really *weird* elephant



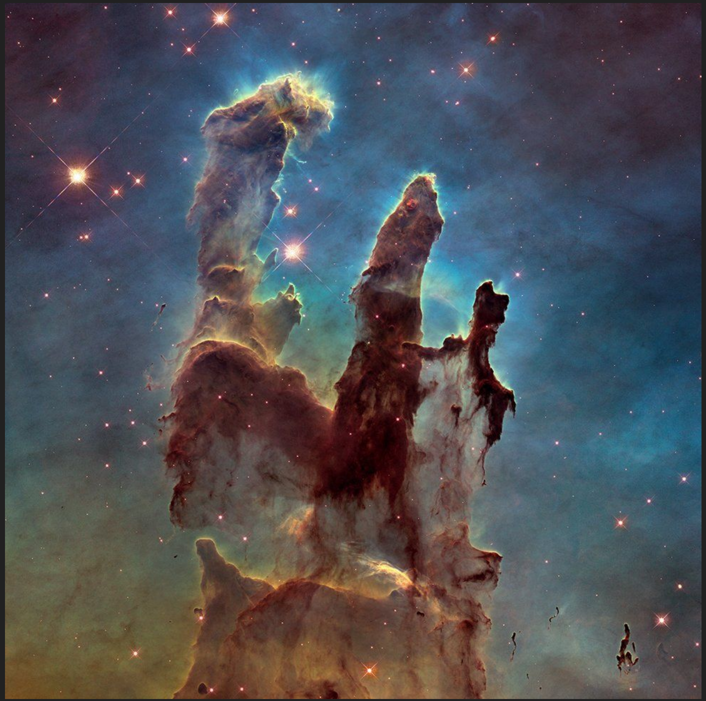
Brout Scolnic, 2021

It’s Dust!

Light passing through dust explains all of these trends!

We know what the cause of these trends is, and we can see its effects in our data!

But we don’t know how much dust there is, or how it changes our observable parameters!



So how dusty *is* the universe?

If we could just see dust, I'd be out of a job.

So instead, we need to figure out a way to model our dust distributions

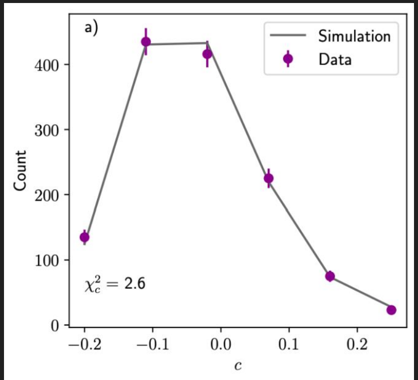
Can't do it analytically - too many variables

Prohibitively time consuming to make new simulations or new universe for each set of proposed parameters

The good news - we have a set of criteria and a way to analyse the impact of different dust distributions!

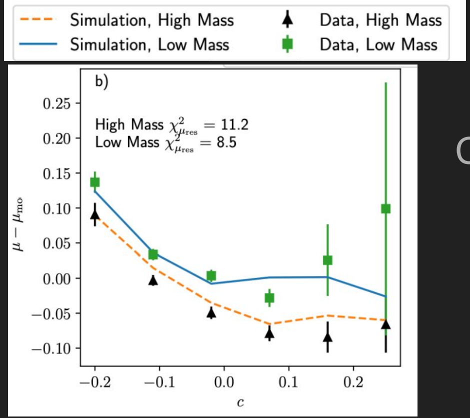
What are our criteria, and why is this so complicated?

Supernova Colour



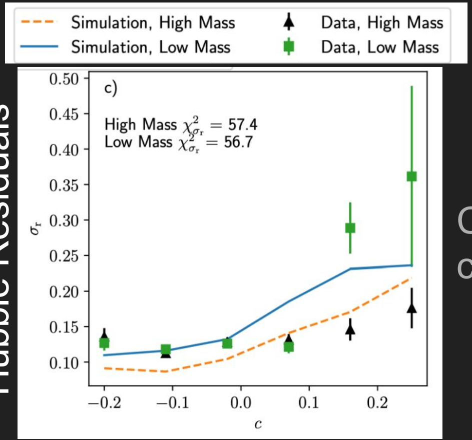
Amount of colour!

Hubble Residuals



Colour vs cosmology!

Scatter in Hubble Residuals



Colour vs. noise in cosmology!

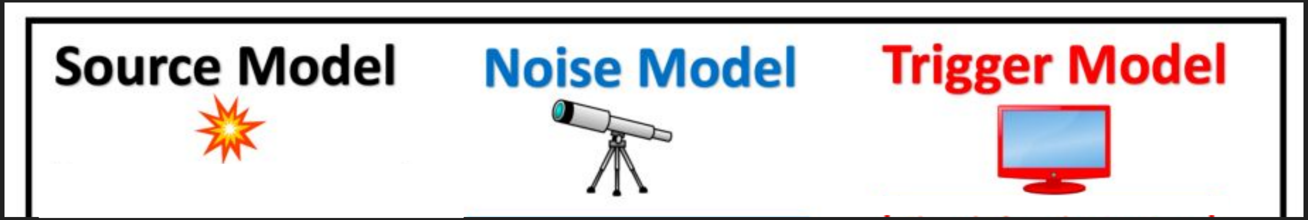
Three big trends with relatively clean signals! But these trends are highly correlated, and we can’t solve for one individually without the others being effected!

Need a holistic approach to modeling these effects

Popovic et al. 2021b

Simulation and Simulacra

So how do we address this? Simulations!



Kessler et al. 2019

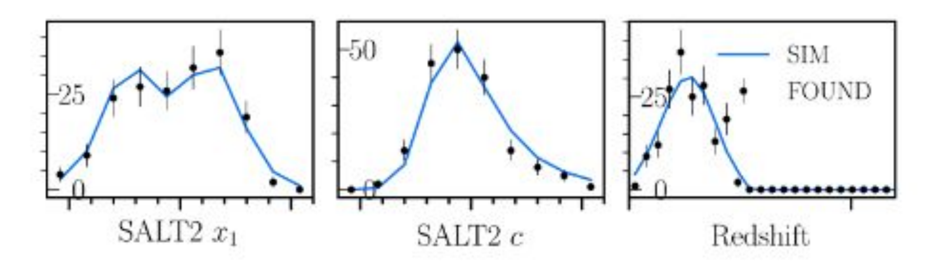
Simulate SNe → Add noise → Detect supernovae

We use Spectral Energy Distributions (SEDs) from observed supernovae to simulate new ones: able to generate a huge variety of SNIa from our relatively small observed sample.

Will be able to do the same thing for Kilonovae!

Why do we need simulations?

- Modeling
  - We can fine tune our theories and test them in real time*, without waiting another 14 billion years
- Statistics
  - As many supernovae as we need, on command
- Known Truth values
  - Can track biases from survey to cosmology
- Validation
  - Check if our theories make sense



Brout, Scolnic, Popovic et al. 2022

Inferring un-observable distributions from observable data

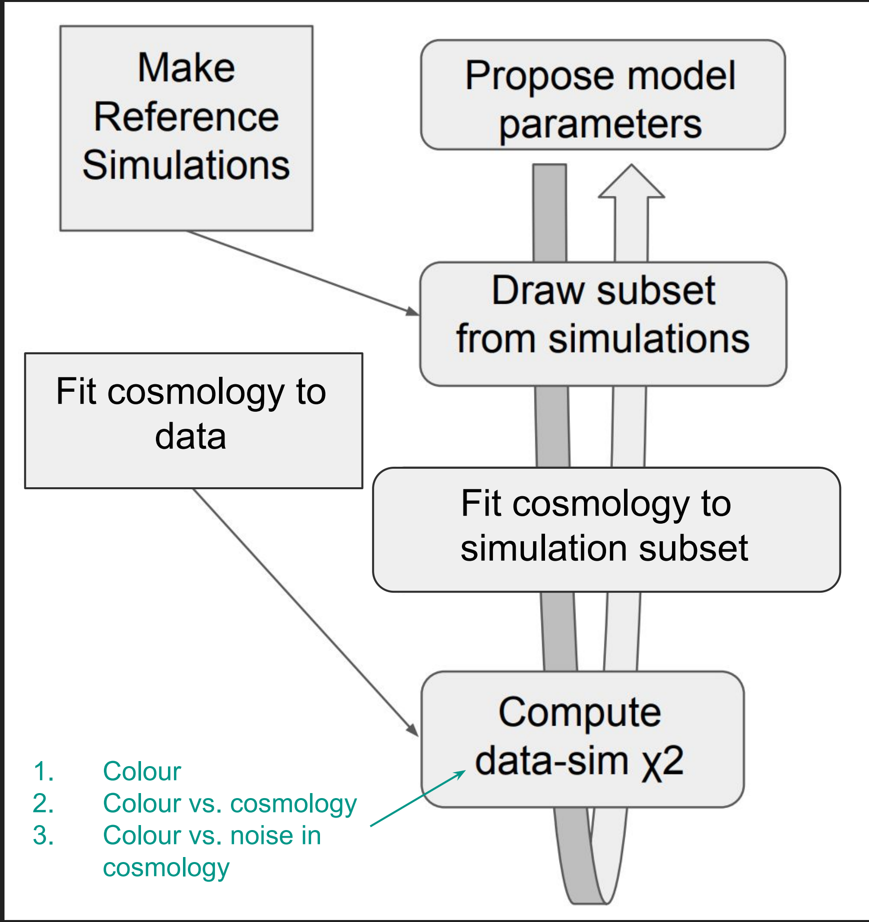
Introducing: Dust2Dust!

A forward-modeling Markov Chain Monte Carlo program!

1. Make one simulation with super relaxed priors
2. Importance sample this large simulation down to match a proposed dust distribution
3. Take this all the way to cosmology for both data and sim
4. Compare using our observable metrics and repeat!

Works because we are able to model known astronomical processes with simulations!

This is the first time the effects of dust on SNIa *including covariances* have been modeled all the way to cosmology!



Popovic et al. 2021b

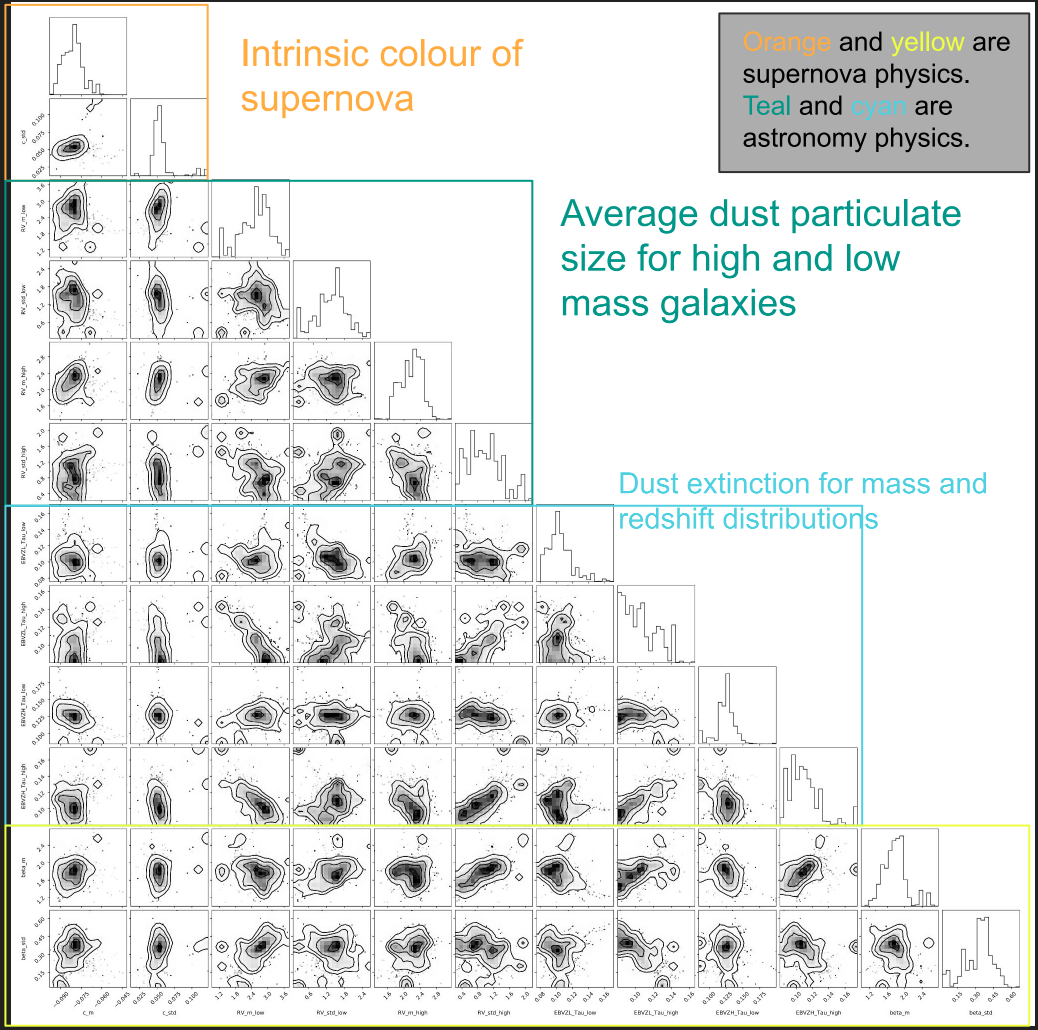
What's the end result of Dust2Dust?

A lot of posteriors!

All this from 3 observable criteria - not bad!

Can compare this to existing literature - average particulate size has been measured for a bunch of galaxies!

New physics hiding in intrinsic colour and colour-luminosity relations



Intrinsic colour-luminosity relationship

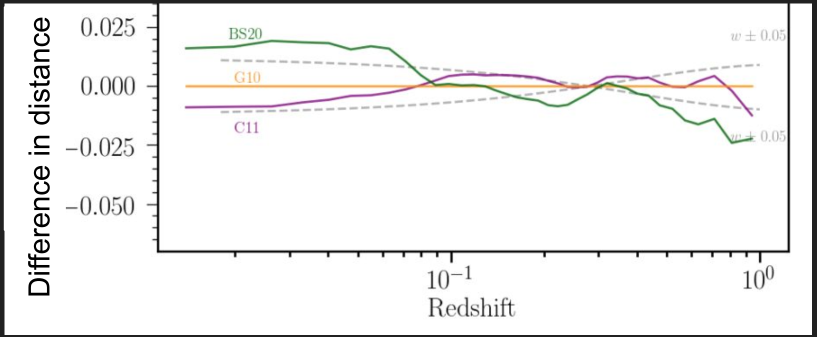
Impact on Cosmology

Pantheon+ results

The difference between a naive, dustless model and a dust-based one is around 10% in w!

This can be reduced down to ~1% when properly modeled and bias-corrected.

The observable effect of these models is degenerate with cosmology - incredibly important to model



Gold and Purple are models without dust!

Conclusion

Modeling population statistics is important for supernovae

We can use these models to identify and reduce biases in our measurements

These models are crucial for breaking w0/wa degeneracy and future breakthroughs in SNIa cosmology

As Gravitational Waves statistics increase, accurate modeling will be necessary to further improve precision

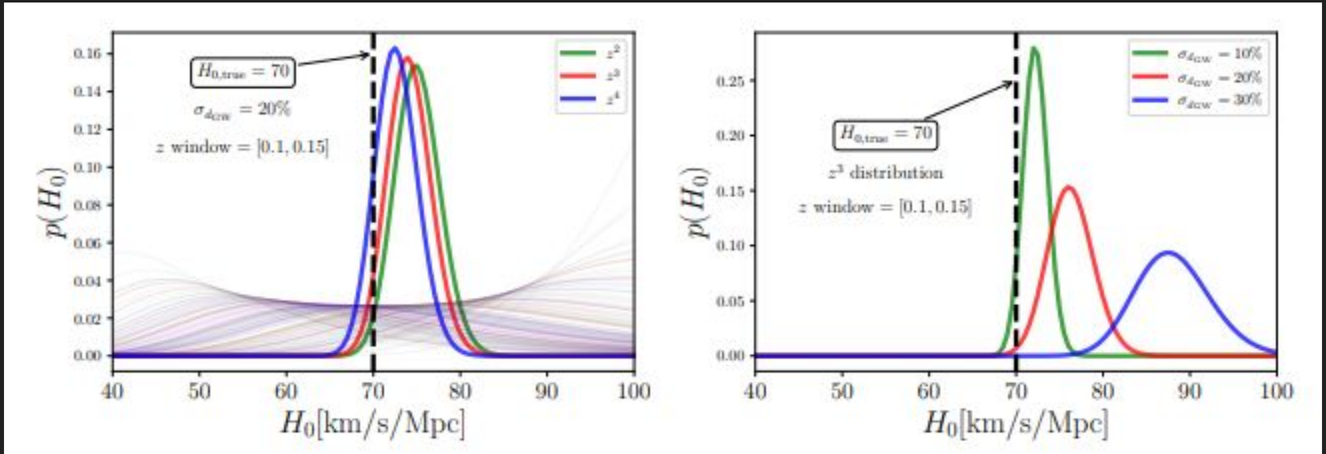
The End

And that brings us all the way back to GW

SNIa cosmology is close to having a systematic-dominated measurement

Reducing these systematics, including modeling astrophysical distributions, is a necessary step to get accurate measurements

This will also become important for GW - a change of only 5 km/s/Mpc is the difference between mystery and banality. GW are likely to be the breakthrough in determining the Hubble Constant in the future



Trott Huterer 2021

Gravitational Waves

Mass gap makes a specific class of progenitor difficult to identify

Easier to address with a redshift

Inclination of the GW along with its relationship to colour goes here.

What variance exists in kilonovae? Are Gravitational Waves standard sirens (mB for supernovae) or standardisable sirens (Tripp equation)

How will we figure out this problem?